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Impact of Antarctic climate during the Late Quaternary: Records from Zub Lake sedimentary archives from Schirmacher Hills, East Antarctica

Badanal Siddaiah Mahesh[a,*], Anish Kumar Warrier[b], Rahul Mohan[a], Manish Tiwari[a]

[a] National Centre for Antarctic and Ocean Research, Earth System Science Organization (ESSO), Ministry of Earth Sciences, Govt. of India, Headland Sada, Vasco 403804, Goa, India

[b] Centre for Climate Studies/Department of Civil Engineering (MIT), Manipal Academy of Higher Education, Manipal 576104, Karnataka, India

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ABSTRACT

The Antarctic continental margin is marked with ice-free areas which are host to numerous freshwater lakes. These lacustrine systems are rich in sedimentary deposits which archive in them the regional and general climatic variations. These lakes respond to the seasonal variations in climate over glacial-interglacial timescales and can be inferred from the sedimentary proxies. In this study, a 79-cm-long radiocarbon dated sediment core retrieved from a peri-glacial lake is analysed for elementary (C_{org}%, N_{org}%), isotopic ($\delta^{13}C_{OM}$, $\delta^{15}N_{OM}$) and particle size (sand, silt, clay). The radiocarbon dated sections (0–65 cm) extends up to 43 kyr BP. The time-series of sedimentary organic matter (OM) proxies ($C_{org} \sim 3.5 \pm 3\%$, $C/N_{atomic\ ratio} \sim 11 \pm 3$ and $\delta^{13}C_{OM} \sim -14 \pm 4‰$) indicate that the OM in this lake sedimentary record is an admixture of terrestrial and lacustrine biomass. Distinctly higher (lower) values during the Holocene (LGM) suggests presence of terrestrial and aquatic (aquatic) biomass indicating ice-free (ice-cover) and warm (cold) Holocene (glacial) conditions which would result in an increased (decreased) lake-productivity and fluvial (wind) input of sand and clay (silt). Higher sand content (~30, ~24 and ~15 kyr BP), silt content (~24 kyr BP), C_{org} and N_{org} (~24 kyr BP) within the Last Glacial Stage (LGS) indicates intermittent warming period in coherence with the Antarctic Isotope Maximum (AIM). The transition in values (C_{org}, N_{org}, C/N ratio, $\delta^{13}C_{OM}$, sand content) starting at 16.6 kyr BP closely following Antarctic deglaciation to reach Holocene optimum values at 11.3 kyr BP documents the influence of Antarctic climate on regional areas.

1. Introduction

Paleo-records reconstructed from the lacustrine sedimentary deposits from ice-free regions along the continental margin of Antarctica are excellent archives in addition to the marine and ice-core records (Tavernier et al., 2014). Due to their proximity to the coast, which is relatively warmer than inland, these lakes respond to subtle seasonal changes and these signatures are archived in the sedimentary deposits. The surface of these lakes freezes during the austral winter (< 0 °C: March to November) while they become ice-free during austral summer (> 0 °C: December to February) exhibiting distinct seasonal variation largely influencing the lake dynamics. During austral winter, the lakes under ice-cover condition are (i) isolated from wind-generated currents (Ragotzkie and Likens, 1964), (ii) cut-off from interaction with the atmosphere inhibiting exchange of gases (Wharton et al., 1986, 1987; Craig et al., 1992), limiting sediment delivery into the lake (Nedell et al., 1987; Wharton et al., 1989; Squyres et al., 1991) and (iv) limited light penetration due to ice-cover resulting in reduced photosynthesis/productivity (Palmisano and Simmons, 1987). The sedimentation in Antarctic lakes is a product of erosional input by glacial melt-water, wind-derived dust, glacier-rafted material and biological productivity. The sedimentary deposits in these pristine lakes are largely undisturbed and hence provide crucial information about the past climate in Antarctica.

The source of organic matter to the Antarctic lakes in the ice-free regions is a product of both autochthonous (algae and cyanobacteria: Yoon et al., 2006; Smith et al., 2006; Hodgson et al., 2009) and allochthonous (lichens and mosses: Heywood, 1972) material. An ice-free open condition is necessary for both wherein the former flourishes as availability of nutrients increases while the latter is introduced into the lake carried by glacial/snow melt-water. Low productivity persists during ice-cover condition throughout the austral winter (Mahesh et al., 2017, 2015), similar to that recorded in sub-glacial and perennially ice-covered lakes (Smith et al., 2006; Hodgson et al., 2009) leading to

* Corresponding author.
E-mail address: mahesh@ncaor.gov.in (B.S. Mahesh).

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generally lower (< 1%) organic carbon content. From the variation in the organic proxies such as C_{org}%, $\delta^{13}C$ and C/N ratios, it is possible to understand the type and source of organic matter that is accumulated in the sedimentary deposits under varying conditions (ice-cover or ice-free) within the lake system. Further, the variation in N_{org} content and $\delta^{15}N$ reveals the lake dynamics (ammonification/nitrification/denitrification: Lu et al., 2010; Xu et al., 2006; Talbot, 2001; Meyers and Teranes, 2001) over glacial-interglacial time-scale.

The input of erosional products to the lake system is predominant during austral summer (Simmons et al., 1986) indicating the significant role of melt-water in transporting the detritus to the lake (Mora et al., 1994; Retelle and Child, 1996; Spaulding et al., 1997). The lakes also receive erosional products in the form of aeolian dust (mid-latitude deserts) carried by the westerlies (Sugden et al., 2009; Petit et al., 1990), wind-transported material from the catchment, along with erosional products deposited by glacier action (Squyres et al., 1991; Hendy et al., 2000).

Considerable number of paleoclimate records have been published from ice-free regions of Antarctic such as Ross Sea region, Wilkes Land, Princess Elizabeth Land, Vestfold Hills, Soya Kaigan region, Larsemann Hills etc. (e.g. Verleyen et al., 2004; Hodgson et al., 2005; Hodgson et al., 2006;Berg et al., 2009; Verleyen et al., 2011; Hodgson et al., 2016; Takano et al., 2012; Matsumoto et al., 2013; Matsumoto et al., 2014; Takano et al., 2015). Very few records are available from the Schirmacher Oasis, Dronning Maud Land (Mahesh et al., 2017, 2015; Warrier et al., 2016, 2014; Phartiyal, 2014; Phartiyal et al., 2011; Krause et al., 1997; Matsumoto et al., 2006).

Here, we report the past changes in variation of the sedimentary-OM by measuring the elemental and isotopic composition along with textural variability in the sediment through grain size analysis to infer variation in past climate and the lakes' response to local and regional climate.

1.1. Site description

More than hundred pristine lakes mark the ice-free region of the Schirmacher Hills which is located in the Dronning Maud Land of East Antarctica (Fig. 1). This isolated land mass of 32 km^2 is marked with low lying-hills which are snow- and ice-free with an average local altitude of 100 m. The lakes in this region are categorized as periglacial-, proglacial-, and epishelf-lakes (Ravindra et al., 2004). Most of the epishelf-and proglacial-lakes are perennially ice-covered, while the periglacial lakes and some proglacial lakes melt during austral summer owing to positive temperature conditions (> 0 °C). Fresh water from snow, glacial melt and melting of permafrost under the soil during austral summer feed these land-locked lakes. These water-bodies cover approximately 3.4 km^2 of Schirmacher Hills. The climate in Schirmacher Oasis is relatively mild due to the low altitude, with air temperature ranging from −7.7 °C to +8.2 °C during mid-summer (December–January) resulting in abundant melt-water streams. The warmest month is January (monthly mean air temperature of 0.7 °C, maximum 8.2 °C), while coldest is recorded during August (monthly mean air temperature of −16.3 °C, minimum −35.5 °C) with an average wind velocity of ~9.7 m/s (Lal, 2006). The rocky terrain of the Schirmacher Hills is dominated by simple vegetation such as lichens and mosses (Rai et al., 2011; Verlecar et al., 1996). The overall organic carbon content in the lake sediments of this region is low which are contributed by faunal groups such as protozoans, nematode tuatis and turbillaria (Rai et al., 2011). The geology is marked primarily by the Precambrian gneiss with felsic variety (Sengupta, 1986) which predominates > 85% of the exposed bed-rocks (Rao, 2000). Other rock types in the area are alaskite, garnet-biotite gneiss, pyroxene granulites, calc-granulites, migmatites, khondalites, enderbites and streaky gneiss intruded by basalt, dolerite, ophiolite, pegmatite and lamprophyre (Sengupta, 1986; Bose and Sengupta, 2003). The rock escarpment in Schirmacher Oasis is devoid of marine terraces or lake terraces or strand lines. This is most likely due the relatively high amount of recent uplift (in the order of 125 m during the last 10 kyr: Hebert and Richter, 1985) north of the boundary of the oasis indicating that the sediments of marine origin are absent in the region. The landforms of Schirmacher Oasis are related to the geological structures as well as the processes of weathering and erosion during the pre-Quaternary and the Ice Age.

The Zub Lake, a periglacial (land-locked) lake which belong to the group of lakes in glacially erosive depression (Loopmann et al., 1986,

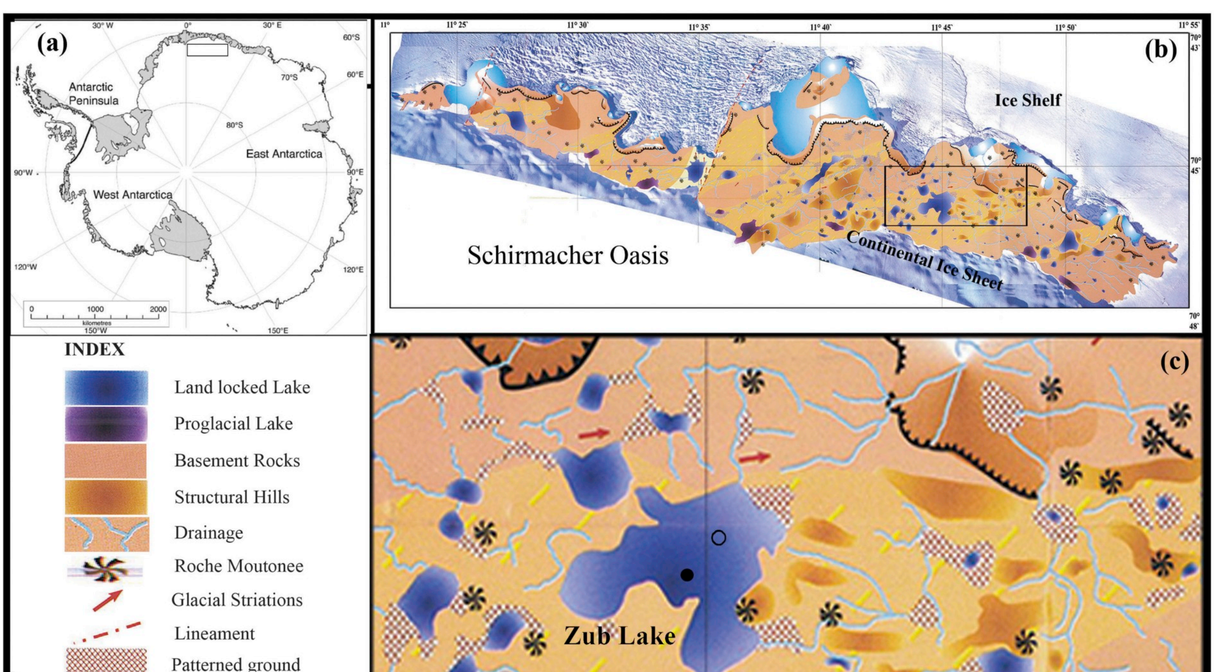

Fig. 1. (a) Map of Antarctica showing the location of Schirmacher Oasis. (b) Geomorphological map (modified after GSI, 2006) of Schirmacher Oasis. (c) Location of Zub Lake (black filled circle).

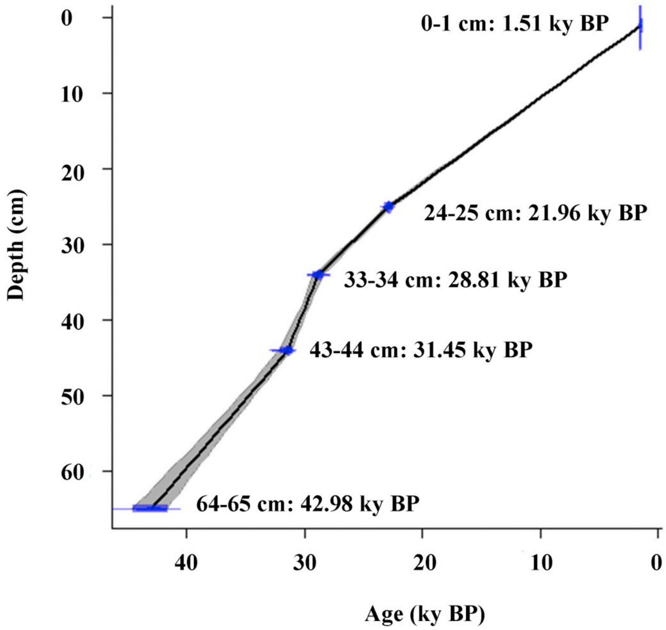

Fig. 2. Age-depth model for Zub Lake sediment core. Calibration of the radiocarbon dates was done using Blaauw (2010). The sedimentation rate is calculated between two adjacent radiocarbon dates.

1988; Richter, 1991; Richter and Bormann, 1995) is located (70°45′48″ S and 11°44′25″ E) in Schirmacher Hills, Queen Maud Land East Antarctica. With an area of about ~0.46 km^2, this lake is located about 0.5 km south of the continental ice-sheet (Fig. 1). It has a maximum water depth of 6 m and is connected with numerous drainage systems which feed the lake with glacial melt-water during austral summer (Heywood, 1972) along with snow melt-water. The *roches moutonéees* (Benn and Evans, 1998) documented in this region gives evidence of glacier influence in the past. The ice-cover over the lake surface during the winter never exceeds 2 m (Hermichen et al., 1985) rendering the sediments largely undisturbed.

2. Material and methods

A79-cm-long sediment core was retrieved from Zub Lake (Fig. 1) during the 28th Indian Scientific Expedition to Antarctica, during austral summer (December 2008). The sediment core was raised from a shallow depth of ~3 m during early summer when the winter ice over the lake still persisted. Percussion method was employed to raise the sediment core in which a core liner encased in a core barrel was manually hammered into the lake sediment bed and the core barrel was retrieved later. After removing the core-liner from the core barrel, the sediment core was immediately stored at −20 °C to prevent disturbance of sediment structures by flushing water. The core was transferred to the National Centre for Antarctic and Ocean Research (NCAOR) under frozen condition. The sediment core was sub-sectioned into 1-cm-slices and freeze-dried for further analysis.

Six sediment samples at different depth intervals were selected for radiocarbon dating. Bulk sedimentary organic matter was selected for radiocarbon analysis as the lake sediment was devoid of biogenic calcium carbonate. The AMS ^{14}C ages for the core were measured at the National Science Foundation-Accelerator Mass Spectrometer facility, University of Arizona, USA. The ^{14}C dates were converted into calendar ages using CLAM program (Blaauw, 2010) and the linear sedimentation rates for the down-core was calculated within the program. Region specific reservoir correction was not available for Schirmacher Hills. Reservoir effect in shallow water lakes such as Lake Zub cannot be detected which is in good agreement with other shallow water lakes of Antarctic Oases (Bird et al., 1991; Kulbe, 1997; Stuiver et al., 1981). Hence, no reservoir correction was applied. The catchment area is devoid of any carbonate bearing rocks. Increases in the "C" by the addition of mineral carbon (graphite, coal, carbonate) from older geological formations due to the geological, climatological and geomorphological conditions are not to be expected (Schwaab, 1998). Hence, the "reservoir age" remains unaltered. One gram sediment from each 1-cm-thick sub-sections of the sediment core were freeze-dried and ground to a fine powder. For C, N and $\delta^{13}C_{OM}$ measurements, aliquots of samples were treated with excess 2 N HCl acid to remove carbonate. After 24 h, the samples were rinsed in distilled water. This step is repeated five times and then samples were oven-dried at 40 °C. Untreated aliquots were used for $\delta^{15}N_{OM}$ measurements (Meyers and Teranes, 2001). We followed the standard procedure of rinse method (Ostle et al., 1999; Galy et al., 2007 and references therein) for preparing the samples for geochemical analysis. We followed the standard procedure of rinse method (Ostle et al., 1999; Schubert and Nielsen, 2000; Galy et al., 2007). The $\delta^{13}C$ and $\delta^{15}N$ were measured at the Marine Stable Isotope Lab (MASTIL) at NCAOR using an Isoprime Stable Isotope Ratio Mass Spectrometer in continuous-flow mode coupled with an EA (Isoprime, Vario isotope cube) The precision obtained for six replicate measurements of C_{org} and N are ± 0.2% and ± 0.3%, respectively (1σ) was determined using the sulfanilamide standard (N = 16.25%; C = 41.81%). The precision on $\delta^{13}C$ and $\delta^{15}N$ is ± 0.02‰ and ± 0.09‰ respectively (1σ standard deviation) obtained by repeatedly running the standards cellulose (IAEA-CH-3: $\delta^{13}C$ value is −24.72‰) and ammonium sulfate (IAEA-N-1: $\delta^{15}N$ value is +0.4‰). Replicate analysis of sample materials gave a precision of ± 0.1% (1 σ). The $\delta^{13}C_{OM}$ and $\delta^{15}N_{OM}$are reported as deviations from international reference standard VPDB and Air respectively. The C/N ratios were calculated for atomic ratios.

For particle size analysis, organic matter and carbonate was removed by pre-treating samples with hydrogen peroxide and glacial acetic acid respectively (Schumacher, 2002). Sodium hexametaphosphate was added before separating sand (> 63 μm) and mud (silt and clay: < 63 μm) fraction using a 63 μ sieve. Silt and clay fraction were analysed using a Beckman-Coulter LS-13320 (0.04e2000 mm). Sand content in weight percent was determined by sieving (Folk, 1980).

3. Results

The age-depth model for the sediment core on calendar-year timescale was obtained by calculating the sedimentation rates between two adjacent radiocarbon dated samples. The sedimentation rates varied between 1.1 cm/kyr and 3.8 cm/kyr (Fig. 2) throughout the core. The highest sedimentation rate (~3.8 cm/kyr) is recorded during the glacial period (28.8 to 31.2 kyr BP).

3.1. *C_{org}, N% and C/N ratio*

The organic carbon content (C_{org}) varies from 0.8% (LGM) to 6.7% (core-top) for the entire 43 kyr BP (Fig. 3) with consistently lower (0.5% avg.) values recorded during the LGS. The organic N content (N_{org}) varies between 0.07% (LGM) and 0.55% with lower (0.06% avg.) values recorded during the LGS. The C/N ratios for the Zub Lake sediment core is predominantly below 10 throughout the glacial period and exceeds values of 10during Holocene (11.3 kyr BP) and at a certain period within the glacial period (~37 kyr BP: Fig. 3).

3.2. *$\delta^{13}C_{OM}$ and $\delta^{15}N_{OM}$ variation*

The$\delta^{13}C_{OM}$ values for the sediment core vary between −18 and −11‰ (Fig. 3). Lowest values (~−18‰) were recorded at 33 and 41 kyr BP (Fig. 3) while the LGM shows depleted values of −14.5‰. The $\delta^{13}C$ exhibits an increase trend during the deglaciation and attains Holocene optimum (−10.3‰) at 11.3 kyr BP. The values show considerable variations (± 3.5‰) throughout the down-core while the glacial period has experienced significant variation of ± 3‰. The

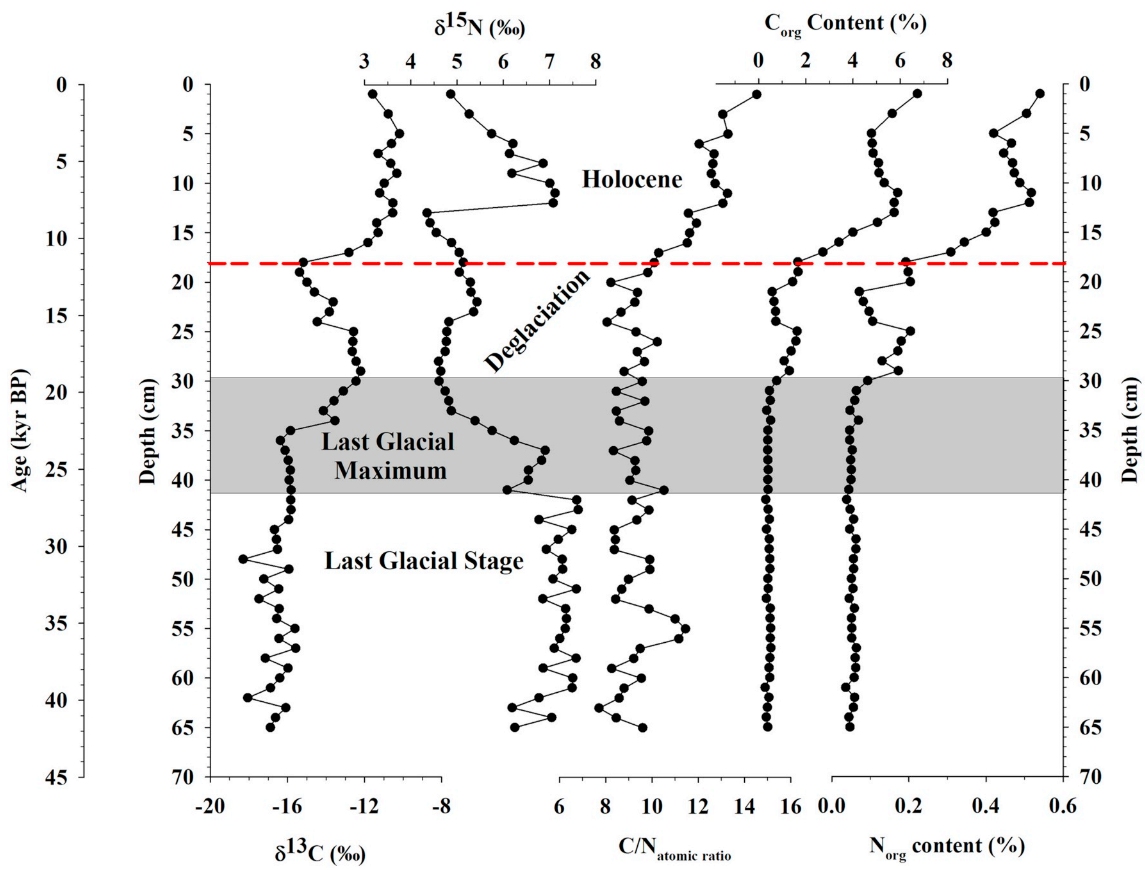

Fig. 3. Down-core variations of elemental (C_{org} and N%), C/N ratios and isotopic ($\delta^{13}C_{OM}$ and $\delta^{15}N_{OM}$) variations for the Zub Lake sediment core for the last 43 kyr BP.

Table 1
Radiocarbon dates for Zub Lake sediment core.

Lab code	Sample Id	Depth	$\delta^{13}C$ (‰)	Conventional AMS ^{14}C age	Error (±)	CLAM 6 ^{14}C yr BP
AA97373	L49(2)-1	0–2	−11.7	1630	36	1513
AA99553	L49(2)-C	24–25	−13.9	18,980	120	21,860
AA97374	L49(2)-D	33–34	−9.8	24,750	200	28,807
AA99552	L49(2)-3	43–44	−11	27,570	290	31,447
AA99555	L49(2)-E	51–52	−17.1	42,900	1700	Rejected
AA99556	L49(2)-F	64–65	−18.6	38,800	1000	42,984

Details of AMS ^{14}C (radiocarbon) dates obtained for selected sections of Zub Lake sediment core. The dates were calibrated using CLAM 2.0 program (Blaauw, 2010). AMS dates were measured on bulk sedimentary organic matter. Calibrated age ranges at 95% confidence intervals.

$\delta^{15}N_{OM}$values range from +4.2 to +7.8‰, with the highest values (+7.4‰) recorded during the LGS (30 to 40 kyr BP) and early Holocene (9.5 to 11.3 kyr BP). The deglacial period and the LGM shows considerably depleted values (~+5‰). The values increase abruptly from lowest values (+4‰) during deglaciation to attain higher values (+7‰) at the beginning of Holocene. The values show significant variation (±2‰) during the LGM and LGS.

3.3. Particle size variation

The sand content varied between 20 and 90% (Fig. 6). The lowest (~22%) values were recorded during the LGM (22 and 25 kyr BP) while the highest is recorded prior to Holocene (14 to 15.7 kyr BP) with an average of 70%. The LGS sand fraction average is 35%. Higher silt content (avg. ~41%) is recorded during LGS with LGM exhibiting higher values (64%) while lower silt content (avg. 12%) is recorded during the Holocene. Significant variation (3 to 25%) is observed within the Holocene. Clay content varies between 3 and 26% with higher values recorded during late Holocene (26%). In general the Holocene records higher values (avg. 22%) while the LGS records lower values (avg. 16%) with significant variation throughout the down-core (Fig. 6).

4. Discussion

The core-top age (0–2 cm) is 1.5 kyr BP while the age of the last dated section (64–65 cm) is 43 kyr BP. One dated section (51–52 cm) has not been used in this study wherein the measure age is > 43 kyr which is most likely due to the presence of older carbon. The age for the core-bottom (78–79 cm) exceeded instrument limits and hence samples beyond 65 cm were not considered for this study (Table 1). The presence of older carbon (~50 cm) suggests the likely presence of glacially eroded tills in the lake sedimentary deposits. Similar deposits were recorded from a sediment core (PG1221: Schwaab, 1998) retrieved from the same lake. Further, another sediment core (L49-1: unpublished data – 1.7 m long) retrieved from the deeper part of the lake shows similar depositions at ~126 cm (8.5 kyr) and 131 cm (18.7 kyr) depth strongly indicating the presence of glacial tills similar to that recorded in PG1221 sediment core between 200 and 240 cm depth. This large difference in depth is most likely because the core L49-1 and PG1221 were collected from the deepest part of the lake while the core L49-2 was collected from a shallower water depth. Also, the algal matter documented in L49-2 is only for the top 10 cm while it is dominant in the top 1 m of the L49-1 core which spans the last ~4 kyr for which studies are being carried out. The glacial till deposits are well documented in L49-1 and PG1221 while it is not easily discernible in the L49-2 sediment core. Hence, at this stage, we are unable to discern with

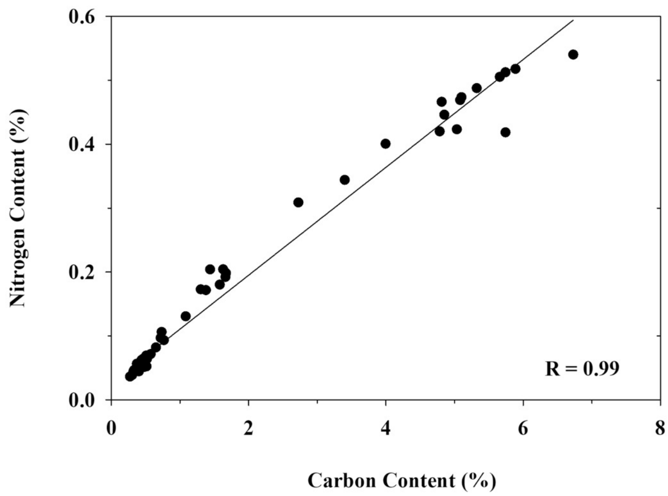

Fig. 4. Scatter-plots of C_{org}% vs. N_{org}% for the Zub Lake sediment core.

confidence the deposition of glacial tills and its associated glaciated state of the Schirmacher Hills as observed in an earlier study.

The type and amount of OM deposited in the lake sediments can be used to the source of OM into the lake and the productivity variation with response to climate (Leng and Marshall, 2004; Meyers, 1997; Talbot and Johannessen, 1992). The C/N ratios in the present time-series vary between 7 and 14 (Fig. 3). The relative proportion of aquatic and terrestrial OM can be understood from the C/N ratios where values < 10 are indicative of algal derived OM while > 20 indicates terrestrial derived OM (Meyers, 1994; Meyers, 2003). The LGS has recorded values below 10 except at ~37 kyr BP (~12) while the Holocene values are consistently above 12 suggesting the dominance of aquatic macrophytes in the former while the latter exhibits an admixture of aquatic macrophytes and terrestrial bryophytes such as lichens and mosses. The C/N ratios of sedimentary OM can also be affected by diagenesis due to differential mobility of C- and N-bearing organic molecules during remineralization. However, the X-Y scatter plots for C_{org} and N_{org} content (Fig. 4) yield statistically significant correlations ($r = 0.99$: $p < 0.0001$) indicating well preservation in sediments (Talbot and Johannessen, 1992). Also, nitrogen correlates linearly with carbon with a positive intercept of N (0.02) suggesting minute but fixed inorganic N backgrounds in bulk N (Jia and Li, 2011) which further indicates that the $\delta^{15}N$ time-series variations are predominantly controlled by organic nitrogen. The general variation of C_{org} and N_{org} are similar indicating a common source suggesting that there is no selective loss of both carbon and nitrogen with time (Talbot and Johannessen, 1992). Also, the bi-plot of C/N ratio versus $\delta^{13}C_{OM}$ confirms that the OM present in Zub lake sediments represents an admixture of aquatic algae and terrestrial biomass (Fig. 5). The OM during the (i) glacial period is predominantly autochthonous (< 10: green filled circles); (ii) deglacial period shows an admixture of aquatic algae and terrestrial end members (10–12: red filled circles), while (iii) Holocene is marked with aquatic algae with significant addition of terrestrial end members such as lichens and mosses (> 12: black filled circles) (Fig. 5).

The sediments of Zub Lake are predominantly made up of clayey sand, silty sand and sandy silt particles as seen in the ternary diagram (Fig. 7). The composition of particles during the three climatic periods (Holocene-Deglaciation-LGS) in the time-series is distinctly different from each other reflecting the prevailing climatic conditions at that time period. The (i) Holocene is predominant with sand and clay (warm climate), (ii) the deglacial stage documents a mixture of sand, clay and silt (transition from cold to warm climate) while (iii) LGS is primarily composed of sand and silt (colder climate) (Fig. 7).

4.1. Climate variation during the deglacial- and last glacial-stage

The C_{org} and N_{org} show minimal variation (± 0.1%) throughout the LGS suggesting an intense cold winter period marked with low productivity. Both the C_{org} and N_{org} shows similar trends and are comparable to that of the values recorded in two different lakes from Schirmacher Hills (Mahesh et al., 2017, 2015). Relatively higher values recorded between 22 and 25 kyr BP is most likely due to a warming period coinciding with the AIM-2. The higher C/N ratios (> 10) recorded at 37–38 kyr BP suggests input of terrestrial macrophytes into an ice-free lake which would have opened up intermittently due to a short warming event which occurred in coherence with the Antarctic warming event (A1: Fig. 8).

The $\delta^{13}C$ values vary between −10 and −18‰ which is within the range of non-marine aquatic plants and algae (−26 to −12‰: Deines, 1980; Farquhar et al., 1989; Fry and Sherr, 1984). The $\delta^{13}C$ values for the LGS shows significant variation (−15 ± 3‰) with depleted values (avg. −16.5‰) recorded between 43 and 29 kyr BP. This is most likely due to the utilization of $^{12}CO_2$ by aquatic organisms resulting in a deposition of ^{13}C-enriched organic matter in the sediments (Meyers and Teranes, 2001). Such a condition exists due to extended ice-cover over the lake inhibiting growth of organic matter which usually is typical of cold glacial stage. The input of terrestrial matter can also result in depleted values but this is very unlikely as the $\delta^{15}N$ values during the same period has recorded enriched values indicating the predominance of aquatic organisms. Low productivity under consistently ice-covered lake surface during the cold glacial period is documented in different lakes of Antarctica (Mahesh et al., 2017; Smith et al., 2006 etc.). Slightly enriched values (−14‰) recorded between 28.8 and 16.6 kyr BP is probably due to a warming event (AIM-2) rendering the lake to open-up enabling higher productivity within the lake due addition of nutrients and air-atmosphere exchange of gases.

The $\delta^{15}N$ values of terrestrial plants which used atmospheric N_2 is lower (0‰) as compared to the nitrate incorporating algae ($\delta^{15}N$ values of 7–10‰: Peters et al., 1978). The $\delta^{15}N_{OM}$ time-series shows significantly large variation throughout the down-core. The LGS (29–43 kyr BP) shows significantly enriched values (> 7‰). Sustained long enriched values during the LGS suggest that the lake was ice-covered limiting lake-to-atmosphere exchange of gases resulting in lower productivity similar to that in the sub-glacial lakes (Smith et al., 2006; Hodgson et al., 2009). Such enrichment of $\delta^{15}N$ generally reflects ammonification and denitrification/nitrification which occurs under ice-cover and mineralization of organic matter by sedimentary and suspended bacteria (Talbot, 2001; Meyers and Teranes, 2001). The $\delta^{15}N$ values shows dramatic decrease from +7‰ (29.6 kyr BP) to +4.8‰ (28 kyr BP) indicating a shift from ice-cover to ice-free conditions more likely owing to the warming (AIM) events during the late LGS.

The episodes of higher sand content within the LGS at 14–16 kyr BP, 23 kyr BP and 29–33 kyr BP closely overlay the warming events i.e., the Antarctic Isotope Maximums (AIM) AIM-1, AIM-2 and AIM-4 (Fig. 8: EPICA Members, 2006). These warming events within the LGS would have resulted in increased melting of glaciers along with rendering the lake ice-free which would lead to enhanced delivery of sand content into the lake. A lower sand content (30%) coincides with the cold event (stadial) between AIM-2 and 4 while the AIM-1 is followed by a minima at ~13 kyr BP coinciding with the Antarctic Cold Reversal (ACR: Fig. 8). The warming events AIM-1, 2, 4 and ACR are well documented in various proxy records from different lakes within the Schirmacher Oasis (Warrier et al., 2014, 2016; Mahesh et al., 2017). The imprints of the general Antarctic climate (EPICA, 2006) are distinctly discernible in the lake sedimentary records indicating that the lakes have well responded to the local climate as well as the general Antarctic climate. The coastal areas of eastern Antarctica are largely influenced by the atmospheric circulation of the inner Antarctic high-pressure area and the deep-pressure swirls of the Southern Ocean. The influence of regional climate is generally dependent on the geographic location,

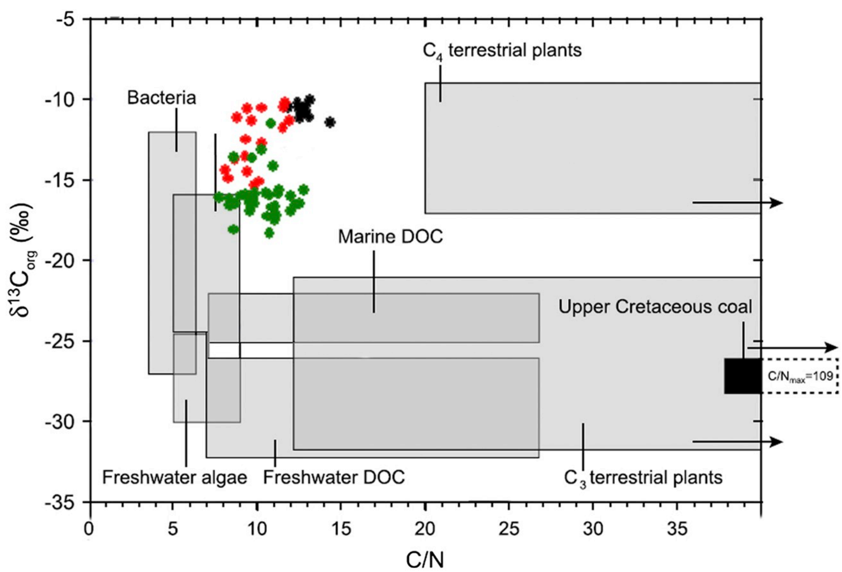

Fig. 5. Bi-plot of C/N ratio vs. $\delta^{13}C_{OM}$ (after Hodgson et al., 2009) for Holocene (red filled circles) and the Last Glacial Stage (black filled diamond). The gray shaded data areas are based on data presented in Meyers and Teranes (2001), Leng and Marshall (2004), and Lamb et al. (2006). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

latitude, elevation above sea level, and distance from the open ocean. At the outset, it can be understood that the lakes in eastern Antarctica responds to the regional climate with strong imprints of the general Antarctic climate. The silt content shows opposite trend to that of the sand content wherein periods of higher silt content is recorded during AIM-4 and -2 indicating enhanced wind delivered detritus to the lake. Higher sedimentation rates (~3.8 cm/kyr) documented during glacial period (28.8 to 31.2 kyr BP) is in coeval with the AIM-4. Associated lowered silt content suggests that the higher sedimentation is primarily due to enhanced delivery of sediment load to the lake through increased glacial melt-water during a brief warming period within the glacial period. The paleo lake-records generated from Schirmacher Hills are of low-resolution as compared to the high-resolution ice-core records and hence a one-to-one correlation is not possible. However, our interpretation is prudent enough in comparing the warm and cold climatic events which are comparable with the ice-core records.

The increase in values in the organic proxies (C_{org}, N_{org}, C/N ratio and $\delta^{13}C_{OM}$) began at ~16.6 kyr BP just after the initiation of deglaciation in Antarctica at 17 kyr BP (Petit et al., 1999). This transition is in coeval with the Antarctic deglaciation suggests that the lake has responded well to the transition from cold-glacial conditions to warm-Holocene conditions. The organic proxy time-series attain Holocene optimum values at ~11.3 kyr BP in coeval with the attainment of full Holocene conditions at 11.7 kyr BP in Antarctica (EPICA Members, 2006). The difference in 400 years recorded in both (LGM-deglaciation and Deglaciation-Holocene boundary) is most likely due to the low temporal resolution of the sediment core as compared to the high-resolution ice-core data. Alternatively, it can be inferred that the Schirmacher Hills took 400 years to respond to the Antarctic deglacial warming. This can be proven by undertaking high-resolution

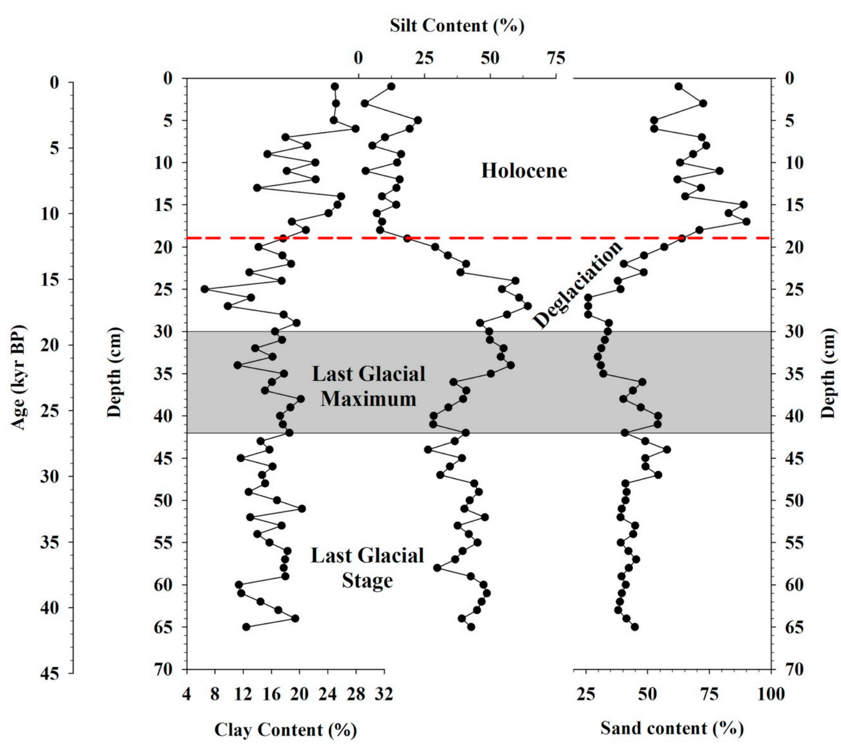

Fig. 6. Down-core variations of particle size variation in the Zub Lake sediment core during the last 43 kyr BP.

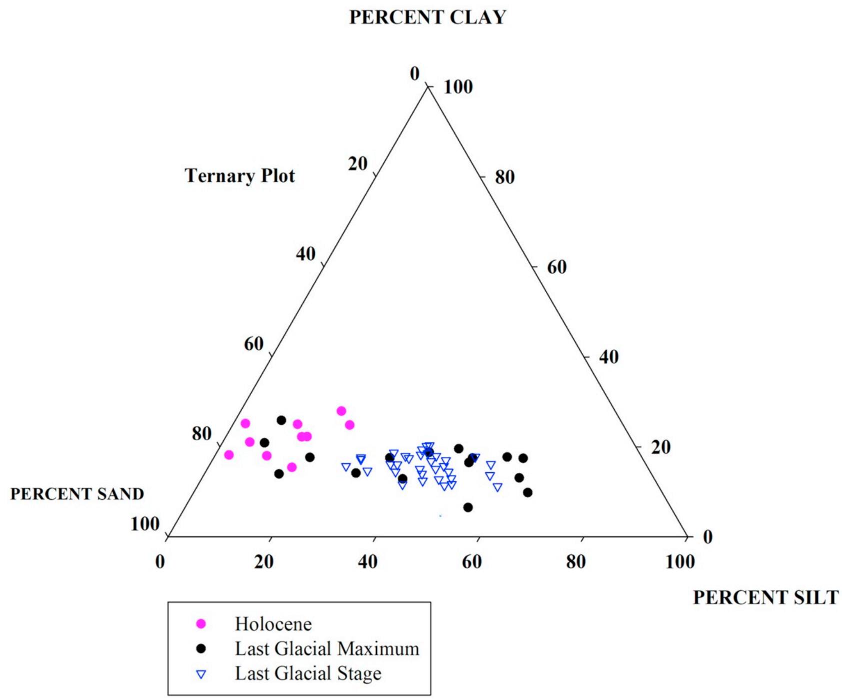

Fig. 7. Ternary diagram comparing the relative (%) sand-silt-clay grain size fractions for sediments from Zub Lake.

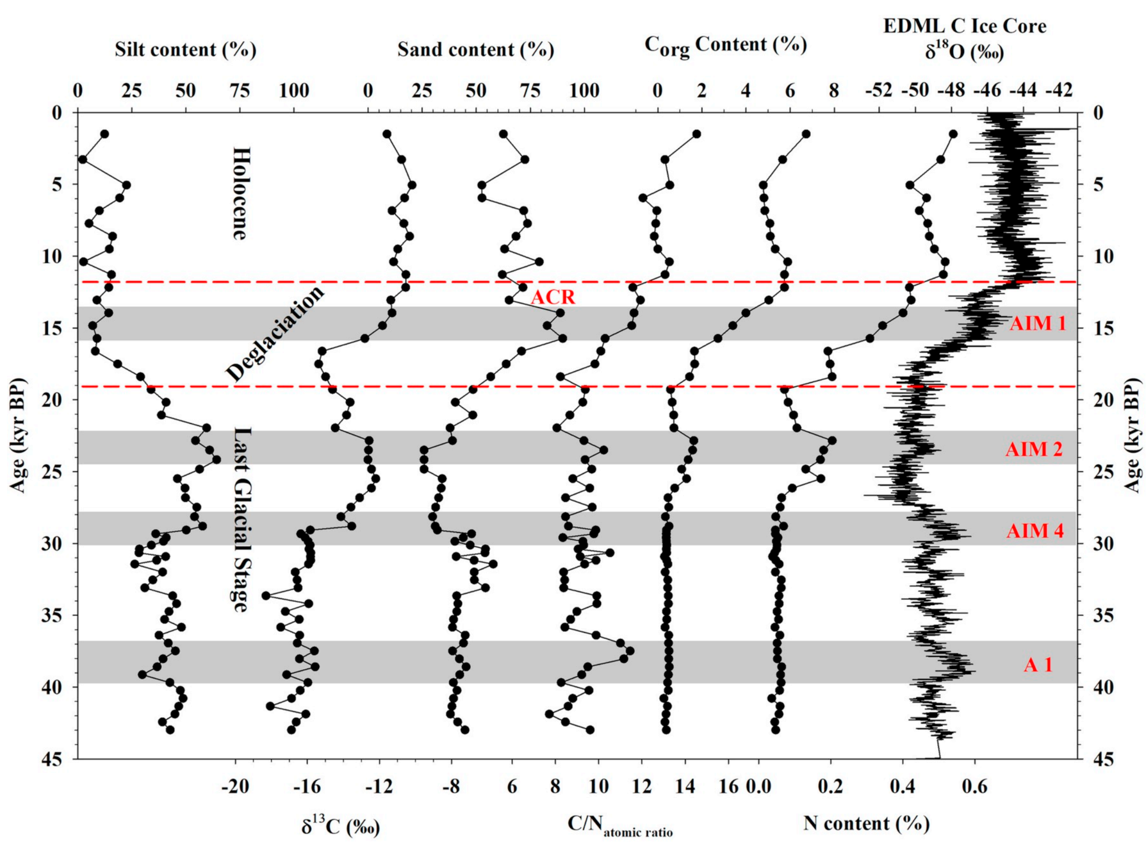

Fig. 8. Comparison of C_{org}, N_{org}, $C/N_{atomic\ ratio}$, sand content, silt content, $\delta^{13}C_{OM}$, EDML C Ice Core ($\delta^{18}O$‰: EPICA Members, 2006) and Vostok Temperature anomaly (Petit et al., 1999). Vertical red dashed lines delimit climatic period (Holocene-Deglaciation-Last Glacial Stage); Gray vertical band represents AIM-Antarctic Isotope Maximum and AI-Antarctic Warming event; ACR-Antarctic Cold Reversal is denoted on Sand content time-series. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

radiocarbon dating on longer sediment cores from the Schirmacher Hills.

4.2. Climate variation during the Holocene

The glacial-interglacial transition in climate is very discrete in the sedimentary proxies. The transition in values (C_{org}, N_{org}, $C/N_{atomic\ ratio}$, $\delta^{13}C_{OM}$, sand content) from the low of LGS (0.3%, 0.05%, < 10, −16‰, ~40%) to higher values (5%, 0.45%, > 10, −10‰, 75%) during the Holocene indicates that the sedimentary archives have documented subtle changes in climatic variation in their depositional environment. Except for $\delta^{15}N_{OM}$, all other proxies (C_{org}, N_{org}, C/N ratio, $\delta^{13}C_{OM}$) attains Holocene optimum at 11.3 kyr BP and sustains throughout Holocene while the former attains higher value (7‰) at 11.3 kyr BP and exhibits decreasing trend reaching lowest value (4.8‰) at core-top. The attainment of consistently higher values during the Holocene suggests a well set warm period with positive temperature (> 0 °C during austral summer) which rendered the lake surface ice-free enabling air-water exchange of gases and addition of nutrients from the surrounding resulting in increased productivity, enhanced delivery of terrestrial organic matter (lichens and mosses) and sediment load (sand and clay content) to the lake through glacial/snow melt-water to the lake basin. The attainment of Holocene optimum values at 11.3 kyr BP is in consistent with the attainment of full Holocene climatic conditions in Antarctica at 11.7 kyr BP (EPICA Members, 2006) suggesting the lakes' response to general Antarctic climate.

The C_{org} and N_{org} show similar trends attaining Holocene optimum (5% and 0.5%) suggesting enhanced productivity in the lake due to extended periods of summer ice-free condition which rendered the lake more productivity due to addition of nutrients. The enriched $\delta^{13}C_{OM}$ (~ −11‰) in the Zub lake time-series from depleted values (~ −16‰) of LGS indicates a shift in the balance of supply/demand on DIC with possible enhanced contribution from the terrestrial OM. The Holocene values are similar to that of the aquatic plants (−26 to −12‰: Deines, 1980; Farquhar et al., 1989; Fry and Sherr, 1984) suggesting a dominance of in-situ productivity along with the addition of terrestrial OM. The $\delta^{15}N_{OM}$ shows decreasing trend during the Holocene indicating a shift in lake environment from an oxygen-depleted (ice-cover) to an oxygen-rich (ice-free) condition. The depleted $\delta^{15}N_{OM}$ values during Holocene suggest the fixation of atmosphere di-nitrogen dissolved in lake water by the cyanobacteria.

The sand and silt content show opposite trends while the clay content shows variation similar to that of the sand. The sand content attains Holocene optimum values (70%) starting at 11.3 kyr BP from highest values of 89% at 15 kyr BP during the AIM-1. The generally higher sand and clay content documented during the Holocene indicates warmer conditions resulting in enhanced glacial/snow melt-water which delivered the detritus to an open lake. The silt content during Holocene shows comparatively lower values (~ −20%) indicating lowered wind delivered detritus.

5. Conclusions

The organic- and inorganic-sedimentary data documents the influence of Antarctic climate in the sedimentary archives of a lake in the ice-free region. The glacial-interglacial shift in climate is well represented in the multi-proxy record and broadly follows the Antarctic ice-core record. The organic sedimentary data reveals that the OM varies between two end-members i.e., autochthonous (aquatic algae) and allochthonous (lichens and mosses). The C/N_{atomic} ratio and $\delta^{13}C$ time-series suggests that the LGS is dominated by the former (ice-cover condition) while the Holocene is a mixture of both the end-members (ice-free condition) suggesting the lake experience consistently ice-free (ice-cover) condition during the Holocene (glacial) owing to consistently (colder) warmer conditions during austral summer. The Antarctic Isotope Maximum (AIM) and Antarctic Warming event (A1) is reflected in the multi-proxy records. Also, the shift in values beginning at 16.6 kyr BP to attain Holocene optimum values at 11.3 kyr BP is in coeval with the Antarctic deglacial trend (17 kyr BP to 11.7 kyr BP) suggesting the response of Schirmacher Hills to the general Antarctic climate. The major climatic events within the Holocene recorded in the ice-core records are poorly represented in the sediments wherein the local climatic signals superimposes on the regional climate signal of East Antarctica.

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